

## **A SIMULATION BASED ANALYSIS OF THE B-1B'S AN/ALQ-161 MAINTENANCE PROCESS**

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### **ABSTRACT**

The Air Force is investigating the use of three levels of aircraft maintenance. This work examines the effect of maintenance resource collaboration and a centralized repair facility on a critical line replacement unit for a major Air Force weapon system. Maintenance data is collected, summarized into probability distributions and used in a discrete event simulation model to examine the impact of changes to the Air Force hierarchical maintenance structure.

### **1 INTRODUCTION**

A remnant of the Cold War era, today's U.S. Air Force (USAF) bomber structure consists of three platforms, the B-1, B-2 and B-52, each filling specific mission niches. Significant resources go into ensuring the mission readiness of each of these weapon systems. The B-1 Bomber is the focus of this study, in particular its avionics repair process. Through use of simulation and modeling, the study shows how to predict the effects of using different maintenance organizational structures for repair processes to the AN/ALQ-161. The effectiveness of repair operations is measured by work in process (WIP) time and machine utilization. Of immediate concern is examining the effects of resource collaborations among units and determining if this has an immediate impact on the availability of the B-1 Bomber weapon system.

The B-1 has an integrated avionics system totaling over 424 installed line-replaceable-units (LRUs) of which there are approximately 212 repairable LRUs. Tentatively, 109 LRUs have been designated for base-level repair on B-1 automatic test equipment (ATE) (Roark 1983), whereas, other repairable LRUs are selected for base-level repair on other support equipment or for depot-level repair. The AN/ALQ-161 ECM, which is the specific focus of this research, consists of roughly 33 LRUs and over 900 single-replaceable-units (SRUs).

The overall USAF maintenance model for aircraft repair involves a hierarchical system of main and sub-components. Main components, the LRUs, are removed from aircraft as required. This rapid removal allows the technician to quickly troubleshoot and isolate any problem with the unit. Furthermore, this LRU modularity permits the technician to replace the LRU immediately should the repair take longer than anticipated. Each LRU is made up of subcomponents called single-replaceable-units (SRUs). These SRUs are replaced as needed to repair the LRU. Effective and efficient maintenance requires a balance between inventory on-hand and the cost of having that inventory. Currently, the average organic (base-level) LRU repair capability of the AN/ALQ-161 is approximately 80%, which means the remaining 20% of LRU repair must be repaired through other resources (either sent to a depot facility or to a contractor). Due to the AF's hierarchical maintenance system architecture, LRU repair capability is only as good as the availability of SRUs on-hand. For this study, we assume sufficient inventories of SRUs to facilitate LRU repair and isolate our investigation on LRUs for the AN/ALQ-161.

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The explicit purpose of this research is to understand and describe any effect of maintenance resource collaboration and a centralized repair facility on the current AN/ALQ-161 LRU maintenance processes and, in turn, the readiness of the B-1B weapon system. The identification of the potential effects of these system enhancements is made possible through the utilization of computer modeling and discrete event simulation.

## **2 BACKGROUND**

The Air Force must provide highly efficient and skilled maintenance to its aerospace weapon systems, such as the B1-B to sustain air superiority. Maintenance tasks are either preventive or corrective in nature and are divided into two categories: on-equipment and off-equipment. On-equipment is the process in which the maintenance task is performed directly on the aircraft, while off-equipment maintenance is carried out on a removed component (DAF 1998). Most Air Force weapon systems are currently repaired at three different levels (DAF 1998): organizational (on-equipment), intermediate (off-equipment), and depot. This is referred to as three-level maintenance (3LM). In 1998, the Air Force, where applicable, mandated a shift towards a two-level maintenance (2LM) concept. In the 2LM system, the intermediate (off-equipment) repair is removed from the process to reduce unit-level maintenance manning requirements and unit-level maintenance costs. The advantages of this particular approach are achieved by leveraging state-of-the-art communications, item visibility, and fast transportation systems. These advantages make it possible for any unserviceable parts to move rapidly to a regional depot or contractor repair process. A regional repair center is a hybrid of 3LM and 2LM systems and combines intermediate level maintenance from multiple bases into one location (DAF 1998). This hybrid approach is known as a Centralized Intermediate Repair Facility (CIRF) and is designed to handle all intermediate repairs while allowing the depot to perform the same type repair it does under the traditional 3LM system.

The CIRF concept is not new; the USAF has periodically experimented with it for the last 60 years. The USAF has at times embraced the centralized concept of aircraft maintenance, and at other times opted for decentralized maintenance, where a preponderance of maintenance actions take place at base-level (Rowe, 2009). Feinberg, et al. (2000). state that the decision to centralize or decentralize maintenance, hinges not on the expected system cost but on the maintenance capacity and operational readiness risk levels the Air Force is willing to accommodate in its operations plans. The recurring success and failures of the CIRF concept is evidenced by discussions found throughout various professional military literature. Ames (2000) concluded the 2LM method did not achieve its projected benefit due to cost overruns associated with transportation. In addition, the maintenance bottleneck experienced at the base-level repair shifted to the depot, where cannibalization of aircraft parts and a steady decline in mission capable rates were a direct result of this shift in maintenance procedures (Ames, 2000). Numerous RAND Project Air Force studies found almost universal support for both overseas and domestic CIRFs (McGarvey et al. 2008). RAND studies posit CONUS-based CIRFs as a cost-effective maintenance strategy. Additionally, they found that the potential manpower cost savings more than offset the increased transportation (shipping) costs. Furthermore, the argument can be made that many existing USAF repair networks already lend themselves toward a CIRF model when measuring cost and performance. Finally, RAND studies concluded that the larger bases are naturally more attractive as CONUS CIRF locations (McGarvey et al. 2008).

### **2.1 Related Logistics Research in Modeling and Simulation**

Many examples exist of successful simulation modeling of both intermediate and depot level maintenance. Shyong (2002) evaluated the effects of various spare parts levels and queuing policies on process time and cost for the overhaul of the F101 LPT rotor at Tinker Air Force Base. Specifically, Shyong demonstrated the value of simulation in evaluating cost and time improvement opportunities in other engine overhaul sub-processes as well (Vigus 2003).

Another example of simulation modeling can be seen in Rodrigues and Karpowicz (1999), as they analyzed the impact of reducing transportation cycle times and consolidating inventories on the operational availability of the Brazilian Navy and Argentine Air Force A-4 fleets. They modeled the repair process of a select aircraft fleet for both countries, providing an effective managerial resource for long-term decision making to improve operational readiness. ARENA software was used to build their model and proved beneficial in establishing the necessary requirements and structure for analysis.

Vigus (2003) used discrete event simulation to assess the impact of process changes to various Programmed Depot Maintenance (PDM) lines for the Coast Guard's HH-60J search and rescue helicopter. Vigus proposed that shorter process times could be achieved by increasing manning to a particular shop in the repair line. The similarity of independent variables and repair system logic provide a solid foundation for model creation and research of the AN/ALQ-161 LRU repair processes.

### **3 METHODOLOGY**

The AN/ALQ-161 maintenance process involves a fairly complex repair network. When LRUs are pulled they are sent to a "back-shop", or intermediate repair facility, for troubleshooting and possible repair. Some LRUs are sent to certain ATE stations where set-up, tear-down, and process times vary dramatically. For this effort, ATE maintenance procedures were assumed homogeneous for all LRUs. Once a LRU is deemed repairable, it proceeds through either one or two ATE stations, depending on LRU type; they are then processed and sent to an appropriate repair station. The final step is the return of the LRU to its original inspection station for a final quality assurance test. LRUs have the potential to fail at any stage in the intermediate repair cycle; at that point, they are declared not-repairable-this-station (NRTS) and are sent to depot for repair.

Behaviors within the aforementioned repair network are described using data collected from the process and reduced using statistics and probability modeling. All the data and information used for this study were received from the B-1 Electronic Warfare Systems Manager (ACC/A4F1). The data provided average repair times and service rates for the number of LRUs produced by each base. LRU arrival rates were based on the number of LRUs per base. Repair averages, with levels at plus and minus 15%, were used in a triangular probability distribution to model repair times. ATE resources were limited, while maintenance personnel were assumed always available for any repair.

Three models were created and used to conduct the analyses. The first model approximates current LRU repair operations at Dyess AFB and Ellsworth AFB, with no collaboration or resource sharing between the two bases. This repair independence approximates the current AN/ALQ-161 LRU repair process and provides baseline results for subsequent analyses. The second model mimics intermediate repair collaboration between the bases, capturing a hybrid-CIRF process. An example of this would involve a LRU that arrives for inspection at a base but transfers to the other base if the present repair queue is too long; in queuing this behavior is known as "balking." Notional transportation times were used for any transfer, however, this study did not include the associated cost. The third model developed completely removed the base intermediate repair capability out of the process and set up a full CIRF to complete the LRU repair. All three models were animated based on adapting models from Mousavi (2010). Animation served to verify proper functioning of the models.

Customer entities are generated using a "Poisson" process based on each base's yearly customer production. Various attributes distinguish the LRU entity including: time of arrival, entity type, inspection time, and repair time based upon their type and location. Once created, the LRU entity routes to a station and is prepared for its initial inspection. Half (4) of the LRUs require one ATE type, the remaining require two. ATE sequencing is not mandatory thus an entity requiring both inspections starts at either ATE. However, LRUs requiring both inspections defaulted to the Defensive Avionics Augmentation Equipment (DAAE) inspection first, while the others are directed to the Radar/Electronic Warfare (R/EW) process. Entity routing mimicked the real-world by using a time delay associated with the removal and transportation of the LRU to a back-shop for repair. All delays used in the model are assumed to be uniformly distributed and are based on expert opinion in such maintenance operations (Figure 1).

Once a LRU is routed to the appropriate ATE station, a decision module is used to discriminate among LRUs repairable at this station (Figure 2). The probability of repair for each LRU was extracted from the original data based on average annual service rate. A failed LRU is considered NRTS, and is routed to the depot for repair. Conversely, a LRU passing inspection is sent to its predetermined ATE station. All repair and inspection times are modeled using a triangular distribution, which is known to provide adequate behavior when distributional aspects of that behavior are unknown or uncertain.

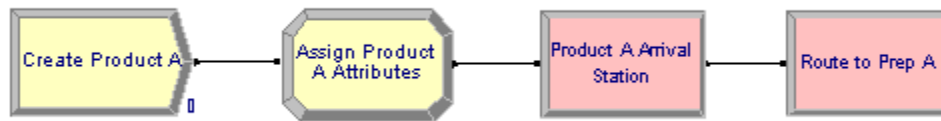


Figure 1: LRU creation, attribute assignment, and routing

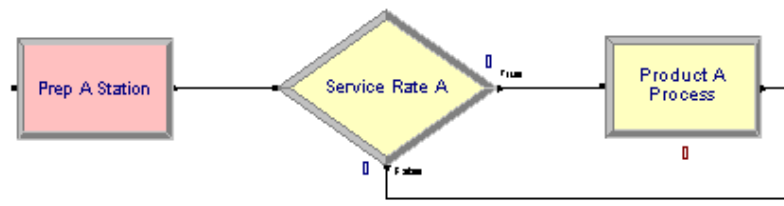


Figure 2: LRU station, probability of service and set-up

The predetermined ATE for each base's 8 LRUs are identical. Tables 1 and 2 provide details:

Table 1: Ellsworth AFB LRU Details

Actual LRU Name	ATE Required	Model Name	Inter-arrival time ( $\lambda$ ) days
TX7 (Bd 7 TX)	R/EW	Product A	4.35
RFS7 (Bd 7 RFS)	R/EW & DAAE	Product B	5.29
RX4-8 (4-8 RCVR)	R/EW	Product C	20.28
ENC (Encoder)	R/EW & DAAE	Product D	11.77
TX5A -6 (Bd 5 Aft TX)	R/EW	Product E	10.14
RFS8 (Bd 8 RFS)	R/EW & DAAE	Product F	9.86
FCH (Channelizer)	R/EW	Product G	19.21
RP (TWF R/P)	R/EW & DAAE	Product H	28.08

Table 2: Dyess AFB LRU Details

Actual LRU Name	ATE Required	Model Name	Inter-arrival time ( $\lambda$ ) days
TX7 (Bd 7 TX)	R/EW	Product A Dyess	5.70
RFS7 (Bd 7 RFS)	R/EW & DAAE	Product B Dyess	5.07
RX4-8 (4-8 RCVR)	R/EW	Product C Dyess	24.33
ENC (Encoder)	R/EW & DAAE	Product D Dyess	16.59
TX5A -6 (Bd 5 Aft TX)	R/EW	Product E Dyess	22.81
RFS8 (Bd 8 RFS)	R/EW & DAAE	Product F Dyess	16.59
FCH (Channelizer)	R/EW	Product G Dyess	19.21
RP (TWF R/P)	R/EW & DAAE	Not produced	Not produced

Each LRU proceeds from its routing station to its required ATE station (Figure 3). There are two inspection stations, R/EW and DAAE, and both stations require one operator resource to operate. The LRU attribute *inspection time*, is used for that particular LRU. The repair lines for both bases are identical. The R/EW ATE model logic is straight forward; LRUs arrive at the inspection station and inspected according to the *repair time* assigned. Immediately, a decision module assesses a probability of repair success. There is a 95% chance of a successful repair. A successful initial repair routes the LRU back for an expedited final inspection before its being returned to its appropriate base supply.

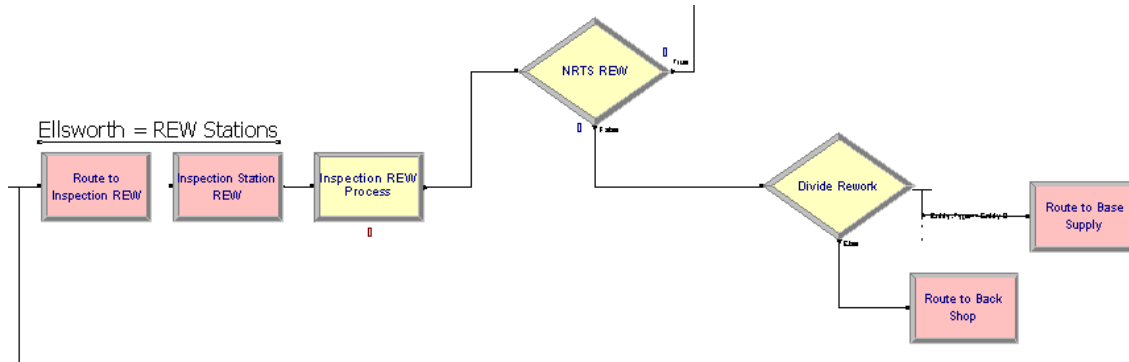


Figure 3: Model 1 R/EW Inspection Station

LRUs requiring two inspection stations can balk. This means, for example, an entity arriving to the DAAE inspection station looks at the number in that queue and compares it to the number in the queue of the R/EW (Figure 4). If the DAAE queue size is greater than one, and the R/EW queue is open, the LRU will balk to the other queue. Both queue length values are notional and were set to facilitate future customization and add an element of common-sense maintenance processes through efficient resource utilization. A LRU that successfully proceeds through the DAAE inspection is then routed to the R/EW station as required.

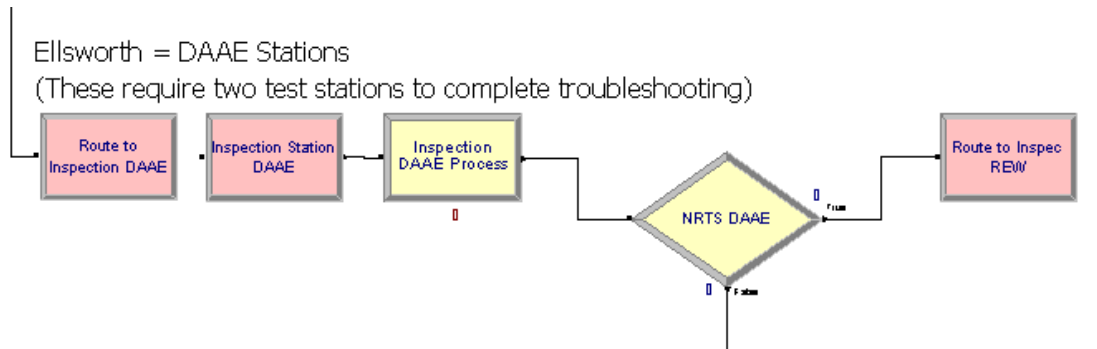


Figure 4: Model 1 DAAE Inspection Station

Once a LRU has completed its respective inspection station requirement it proceeds to the back shop (Figure 5). This back shop repair process is similar to the inspection process and is based upon the average LRU *repair times* assigned earlier in the model. Notably, new and reduced inspection times are assigned to entities. LRUs return to inspection stations based upon their entity type. LRUs under re-inspection have higher priority than items in the queue and shorter inspection times.

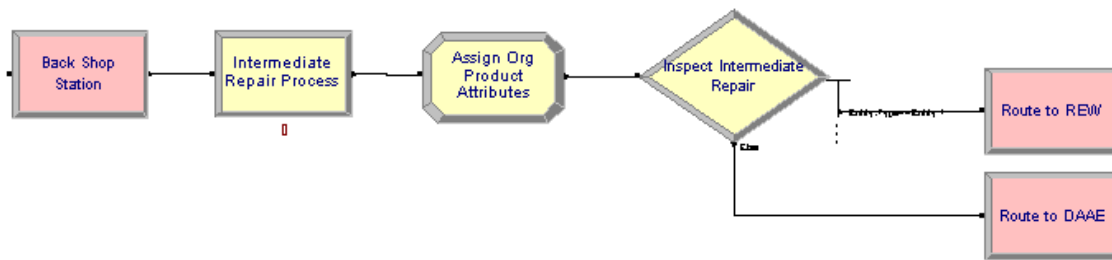


Figure 5: Model 1 Back-shop Repair Process

Finally, the repaired LRUs return to base supply based upon the new entity type that was assigned after the repair process. Model 2 is very similar in process flow to Model 1, but differs in that system resources are shared.

The third model simulates the full CIRF concept (Figure 6). Within CIRF, all intermediate repair processes, such as inspection and repair, are removed from the base level repair network and transferred to the CIRF.

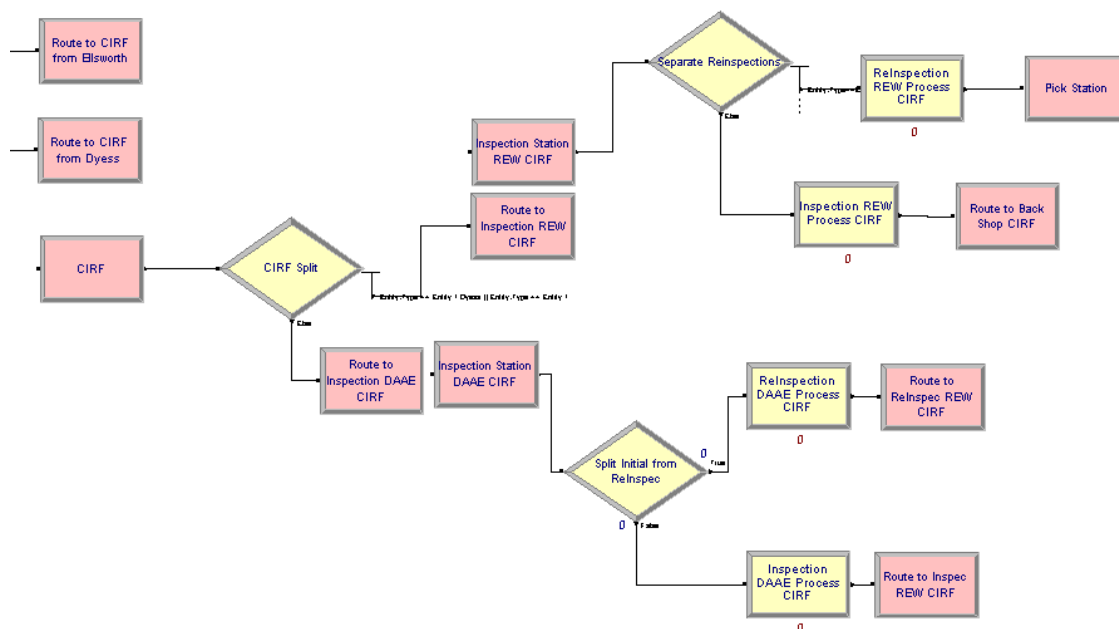


Figure 6: Model 3, CIRF Repair Process

After the repair process for the CIRF, a new entity attribute is assigned along with new and shorter inspection times (Figure 7). As seen in the other two models, the repaired LRU's take precedence in the queue during the re-inspection process. The Appendix contains screen shots of the model animations.

All three models begin in the **“empty-and-idle”** state; no entities created yet and all resources are idle (Kelton et al., 2007). This empty-and-idle state is not reflective of normal operations, thus the simulation must execute for a period of simulated time to a point where it depicts normal operating conditions. This period of execution is referred to as the “warm-up” period. However, determining the warm-up period is not an exact science, Kelton et al. (2007) recommends using one of two different techniques. The first technique is to establish a single overall output performance measure (such as work in progress (WIP)) and monitor its output during simulation runs. Eventually, there is a period when the measure reaches a steady state. A process is in steady state when its measure of performance, such as average WIP, has

settled down to some value (usually close to its long-term expected value). This steady state point defines the initial warm-up period. The second technique runs the model for such a long period of time that any potential bias caused by the warm-up period is overwhelmed by the amount of later data (Kelton et al., 2007). For all three models, a warm-up period of five days was used with all data from the warm-up period deleted from the overall measurement calculations.

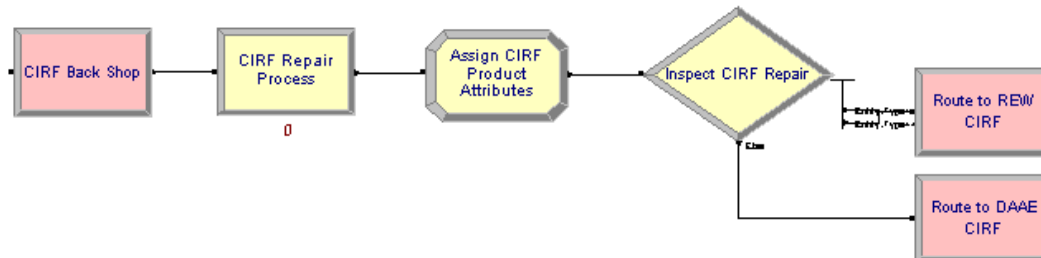


Figure 7: Model 3 CIRF repair process and routing

A total of 20 different scenarios were used to analyze three maintenance structures. The variations used are shown in Table 3 and Table 4. ARENA's Processor Analyzer Tool was employed to quickly modify the resources within each computer experiment, run the experiment, collect the data, and compare the results. In all three models, the baseline is the initial condition where all resources (R/EW, DAAE and repair stations) are set to a level of one. Different combinations of resources define each unique scenario. Each iteration produced results that are compared against the baseline to determine levels of significance. The best scenario for each model was then selected.

Table 3: LRU Scenarios for Models 1 & 2

Scenario	Ellsworth		Dyess		Both	
Model 1	+1 repair	+2 repair	+1 repair	+2 repair	+1 repair	+2 repair
Model 2	+1 repair	+2 repair	+1 repair	+2 repair	+1 repair	+2 repair

Table 4: LRU Scenarios for Model 3

Scenario	Repair Station		Inspection Station	Both	
Model 3	+1	+2	+1 R/EW & +1 DAAE	+1	+2

#### 4 RESULTS AND ANALYSIS

The experiment involves a hypothesis designed to examine what maintenance configuration may contribute to an overall improvement in WIP and machine utilization. Given outputs from simulations of the two alternatives, the hypothesis is:

$$H_0: P_1 - P_2 = 0$$

$$H_a: P_1 - P_2 \neq 0$$

Where:  $P_1$  = total average WIP for scenario 1, and  $P_2$  = total average WIP time scenario 2. The null hypothesis,  $H_0$ , assumes no difference exhibited in WIP times between scenario 1 and scenario 2. If the test rejects the null hypothesis, there is a significant difference in WIP times and the alternate hypothesis is accepted. However, if the hypothesis test fails to reject the null, no conclusion regarding the alternate can be made (Vigus 2003).



A paired t-test was accomplished due to unequal variances of all scenarios output. This test produces confidence intervals for the difference of means. The test fails to reject the null hypothesis when the confidence interval “hooks zero” (Vigus 2003). Furthermore, equal sample sizes were used for all three models.

Additionally, the null hypothesis was rejected when a confidence interval exists that does not contain 0, which supports the conclusion that the differences in mean outputs are statistically significant between scenarios 1 and 2.

#### 4.1 Work In Process

Initial WIP times for each model’s baseline are shown below (Figure 8). For all cases, the upper line (red) represents WIP times for Ellsworth AFB and the lower line (green) is Dyess AFB.

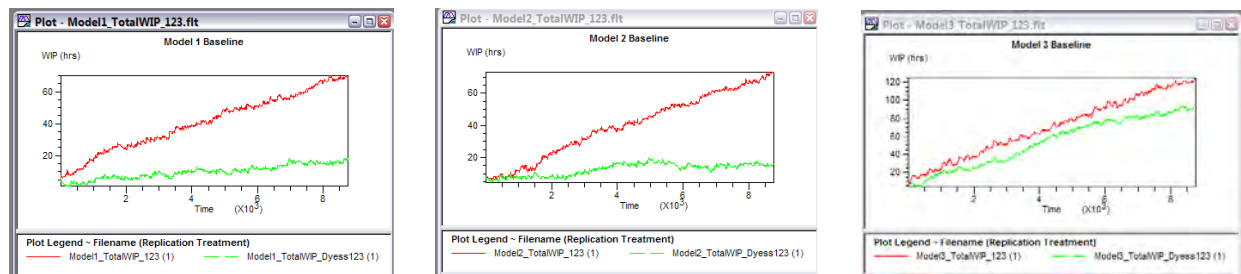


Figure 8: Baseline WIP for all Models

ARENA's output and process analyzer utilities were used to test for significance between each scenario. In all 20 scenarios, an individual confidence interval of 95% was used in the selection of the best case scenario. Finally, total WIP was calculated from the simulation statistic function in ARENA, producing the results for the three models by scenario (Table 5). The largest return on investment for all three models was evident when resources were added to a repair station. For Models 1 and 2, adding resources to the Ellsworth AFB repair station had the greatest benefit from an enterprise viewpoint.

#### 4.2 Machine Utilization

Machine utilization for each scenario was calculated using the ARENA's process analyzer. This utility creates scenarios by changing resource levels and giving model output for comparison. Table 6 shows the results obtained, in which scenarios 1, 8 and 15 are the baseline for each of the models. In addition, values of 1 demonstrate a resource operating at maximum capacity. The best results for Models 1 and 2 were apparent when two repair stations were added to both Ellsworth AFB and Dyess AFB. In Model 3, the most significant gain in machine utilization came from adding two resources to everything. This included R/EW and DAAE inspection stations as well as the CIRF repair station. It should be noted adding two repair stations to the CIRF model gave a comparable result to Model 1 and 2, for half the resources required.

### 5 CONCLUSIONS

This research utilized high level computer simulation to help predict the impact of different maintenance organizational structures on the LRU repair of the AN/ALQ-161. The two measures of effectiveness used were work in process time and machine utilization.

Table 5: Total WIP by Scenario

Scenario	Model 1 Dyess	Model 1 Ellsworth	Model 2 Dyess	Model 2 Ellsworth	Model 3 Dyess	Model 3 Ellsworth
01-Model 1: Baseline	7.63	38.4	---	---	---	---
02-Model 1: +1 Repair to Ells	6.97	2.54	---	---	---	---
03-Model 1: +2 Repair to Ells	8.16	2.29	---	---	---	---
04-Model 1: +1 Repair to Dy	2.09	32.39	---	---	---	---
05-Model 1: +2 Repair to Dy	1.98	34.46	---	---	---	---
06-Model 1: +1 Repair to both	2.14	2.59	---	---	---	---
07-Model 1: +2 Repair to both	1.95	2.28	---	---	---	---
08-Model 2: Hybrid CIRF	---	---	10.15	36.66	---	---
09-Model 2: +1 Repair to Ells	---	---	6.34	2.59	---	---
10-Model 2: +2 Repair to Ells	---	---	6.96	2.3	---	---
11-Model 2: +1 Repair to Dy	---	---	1.79	31.11	---	---
12-Model 2: +2 Repair to Dy	---	---	1.66	35.24	---	---
13-Model 2: +1 Repair to both	---	---	1.79	2.52	---	---
14-Model 2: +2 Repair to both	---	---	1.65	2.32	---	---
15-Model 3: CIRF	---	---	---	---	53.66	71.33
16-Model 3: +1 Repair	---	---	---	---	7.81	10.84
17-Model 3: +2 Repair	---	---	---	---	7.1	9.94
18-Model 3: +1 REW +1 DAAE	---	---	---	---	48.85	63.34
19-Model 3: +1 to everything	---	---	---	---	7.5	10.29
20-Model 3: +2 to everything	---	---	---	---	6.89	9.62

Resource sharing between Ellsworth AFB and Dyess AFB brought forth both advantages and disadvantages to their respective maintenance processes. The main advantage recognized in the Model 2 baseline was decreased machine utilization for both inspection stations at Dyess AFB. The DAAE inspection machine utilization went from 30% to 19%, while R/EW machine utilization went from 39% to 21%. Additionally, 123 LRUs were shipped from Ellsworth to Dyess, thus facilitating resource collaboration and helping to more evenly distribute the workload for both bases. However, some of the shortcomings with this approach include; the costs associated with shipping LRUs between bases, the management of assets in route increases system complexity, and having multiple process owners tends to increase concerns.

Implementing the Centralized Intermediate Repair Facility (CIRF) for all ALQ-161 LRUs has benefits as well as certain drawbacks as well. The first advantage recognized in Model 3, was the simplicity of the model 3 logic when compared to that of models 1 or 2. Surprisingly, however, WIP baseline times for LRU repair at the CIRF were dramatically higher in all cases. A significant reduction in cost associated with the consolidation of resources and personnel is certainly an advantage of the CIRF process. While cost and manpower were not a focus in this study, it is easy to see that a single process owner and enterprise focus on repair management is advantageous.

The lack of empirical data was a limiting factor, however all three models were created based on actual processes and driven by real-world data. Notably, notional distributions had to be used in order to scope the high level of complexity. The best process configurations for each model scenario employed or examined are shown in Table 7. The best LRU repair network set-up for each model is illustrated with regard to the performance measurements of WIP and machine utilization.

Table 6: Machine utilization by scenario

Scenario	Repair Station Ells	Repair Station Dyess	R/EW Ells	R/EW Dyess	DAAE Ells	DAAE Dyess	Repair Station CIRF	R/EW CIRF	DAAE CIRF
01-Model 1: Baseline	1	0.99	0.25	0.39	0.22	0.3	---	---	---
02-Model 1: +1 Repair to Ells	0.66	0.98	0.29	0.39	0.25	0.29	---	---	---
03-Model 1: +2 Repair to Ells	0.44	0.99	0.29	0.39	0.25	0.29	---	---	---
04-Model 1: +1 Repair to Dy	1	0.52	0.25	0.4	0.22	0.3	---	---	---
05-Model 1: +2 Repair to Dy	1	0.34	0.26	0.4	0.21	0.3	---	---	---
06-Model 1: +1 Repair to both	0.67	0.52	0.3	0.41	0.25	0.31	---	---	---
07-Model 1: +2 Repair to both	0.43	0.33	0.29	0.39	0.24	0.29	---	---	---
08-Model 2: Hybrid CIRF	1	0.99	0.26	0.21	0.23	0.19	---	---	---
09-Model 2: +1 Repair to Ells	0.68	0.99	0.3	0.21	0.25	0.18	---	---	---
10-Model 2: +2 Repair to Ells	0.44	1	0.3	0.21	0.24	0.19	---	---	---
11-Model 2: +1 Repair to Dy	1	0.52	0.26	0.21	0.21	0.2	---	---	---
12-Model 2: +2 Repair to Dy	1	0.34	0.26	0.21	0.21	0.19	---	---	---
13-Model 2: +1 Repair to both	0.67	0.52	0.29	0.21	0.25	0.2	---	---	---
14-Model 2: +2 Repair to both	0.45	0.34	0.3	0.21	0.24	0.2	---	---	---
15-Model 3: CIRF	---	0	0	---	---	---	1	0.42	0.2
16-Model 3: + 1 Repair	---	0	0	---	---	---	0.81	0.53	0.32
17-Model 3: +2 Repair	---	0	0	---	---	---	0.54	0.53	0.32
18-Model 3: +1 REW +1 DAAE	---	0	0	---	---	---	1	0.21	0.1
19-Model 3: +1 to everything	---	0	0	---	---	---	0.83	0.27	0.16
20-Model 3: +2 to everything	---	0	0	---	---	---	0.55	0.18	0.11

A APPENDICES

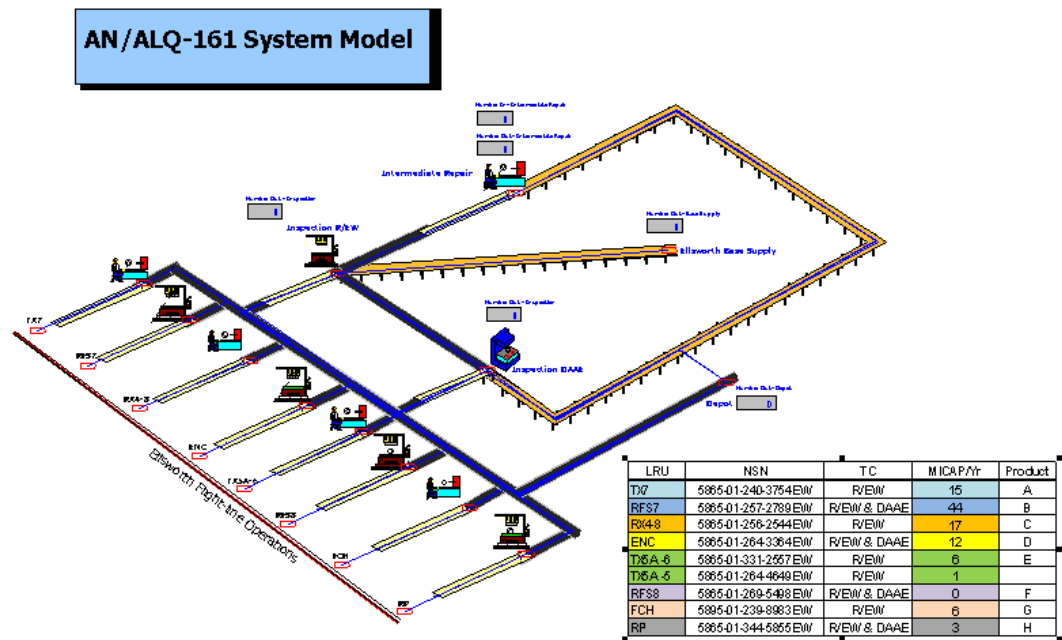


Figure A-1: Model 1, Independent Bases

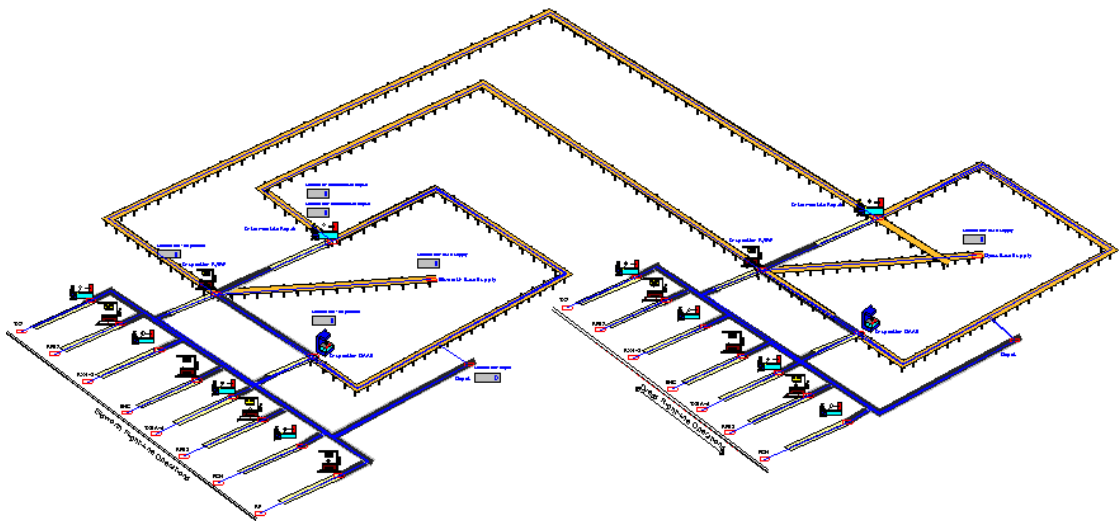


Figure A-2: Model 2, Hybrid CIRF Concept

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